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14. ABSTRACT

The programmable surfaces project has investigated programming momentum transfer across surfaces for novel forms of robotic mobility. It studied cells for controlling shear and normal flows, structural systems for reversible construction, deformable actuated ultralight materials, and automated assemblers. The results offer new ways to build robots, and new ways for robots to build.

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Report Title

Programmable Surfaces

ABSTRACT

The programmable surfaces project has investigated programming momentum transfer across surfaces for novel forms of robotic mobility. It studied cells for controlling shear and normal flows, structural systems for reversible construction, deformable actuated ultralight materials, and automated assemblers. The results offer new ways to build robots, and new ways for robots to build.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
03/30/2014	3.00	K. C. Cheung, N. Gershenfeld. Reversibly Assembled Cellular Composite Materials, Science, (08 2013): 0. doi: 10.1126/science.1240889

TOTAL: 1

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

08/19/2012 1.00 Ara N. Knaian, Kenneth C. Cheung, Maxim B. Lobovsky, Asa J. Oines, Peter Schmidt-Neilsen, Neil A. Gershenfeld. The Milli-Motein: A Self-Folding Chain of Programmable Matter with a One Centimeter Module Pitch,
IEEE/RSJ International Conference on Intelligent Robots and Systems. 07-OCT-12, . : ,

TOTAL: 1

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received | Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME | PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Post Doctorates

NAME | PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Faculty Supported

NAME | PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Under Graduate students supported

NAME | PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

see attachment

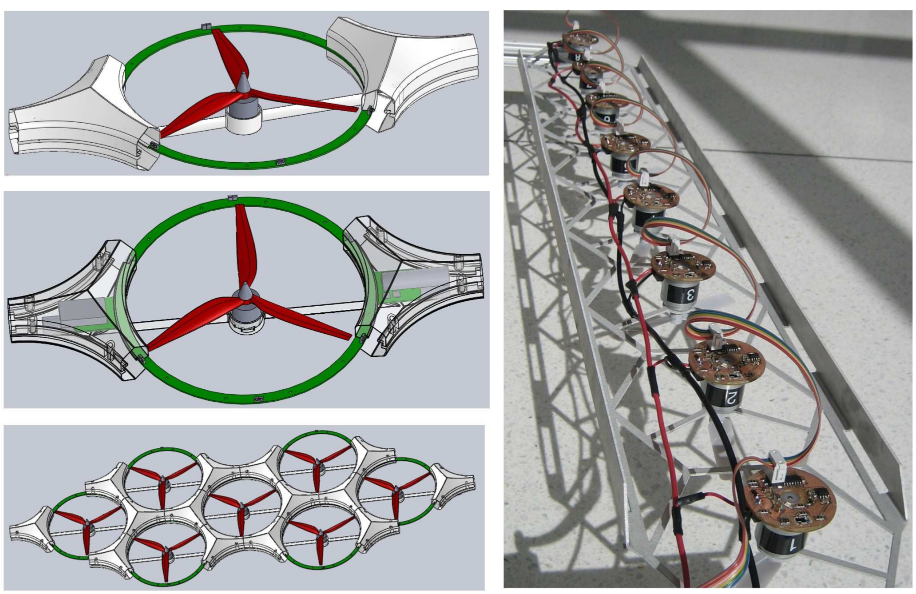
Technology Transfer

Programmable Surfaces

M3: Maximum Mobility and Manipulation
W911NF-11-1-0096
The Center for Bits and Atoms
MIT
Final Report

March 30, 2014

The programmable surfaces project grew out of earlier work by the project team on programmable matter, which developed the mathematics of coded folding [*Programmable Assembly With Universally Foldable Strings (Moteins)*, Kenneth C. Cheung, Erik D. Demaine, Jonathan R. Bachrach, and Saul Griffith, *IEEE Transactions on Robotics* (27:4), pp. 718-729 (2011)], electropermanent actuators for high torque at low RPM with static holding [*Electropermanent Magnetic Connectors and Actuators: Devices and Their Application to Programmable Matter*, Ara Knaian, *Ph.D. Thesis, MIT* (June 2010)], and combined these to create the smallest pitch chain robot [*The Milli-Motein: A Self-Folding Chain of Programmable Matter with a One Centimeter Module Pitch*, Ara N. Knaian, Kenneth C. Cheung, Maxim B. Lobovsky, Asa J. Oines, Peter Schmidt-Neilsen, and Neil A. Gershenfeld, *IEEE/RSJ International Conference on Intelligent Robots and Systems* (2012)].

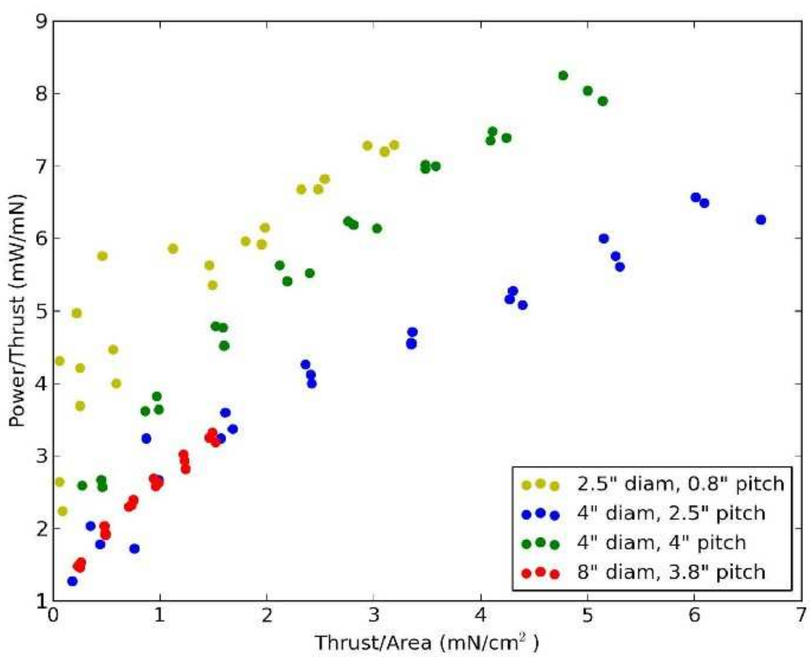


Programmable surface cells

Programmable surfaces sought to program momentum transfer across surfaces rather than through volumes, for novel forms of robotic mobility. It first investigated shear forces with arrays of rollers in water, then focused on normal forces with arrays of fans in air [*Programmable Surfaces*, Amy Sun, *Ph.D. Thesis, MIT* (February 2012)].

Wind tunnel measurements on an instrumented networked fan array

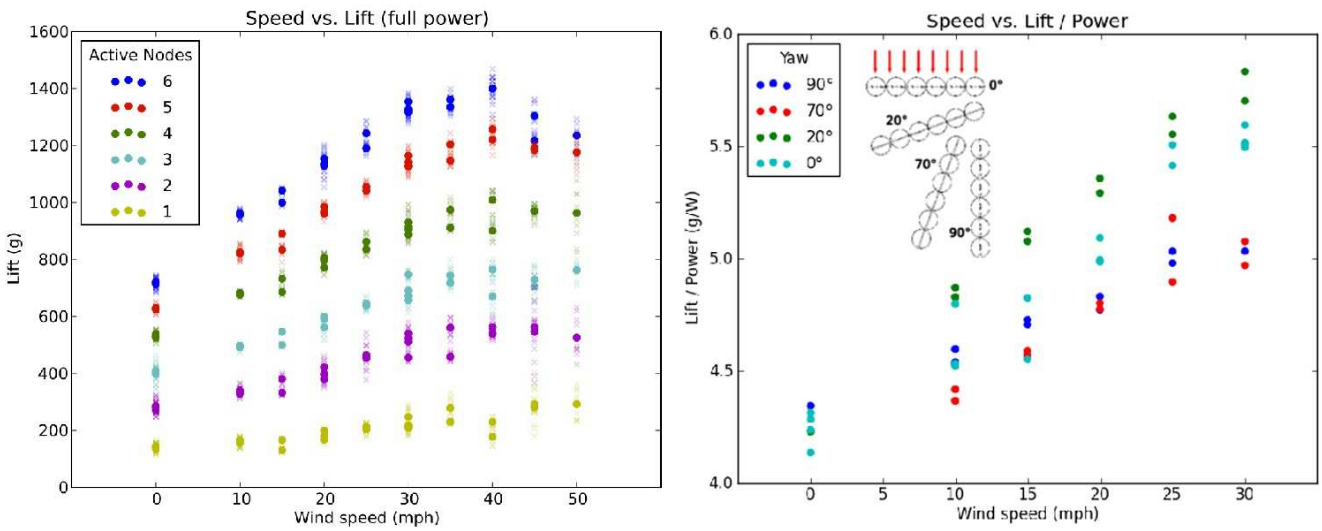
These studies were done in support of developing an "N-copter": a modular lift cell that can transfer power, data and forces and be assembled arbitrarily to match a mission. Goals include enhancing safety, reliability, and scalability over fixed-function UAVs.



Lift cell efficiency versus size

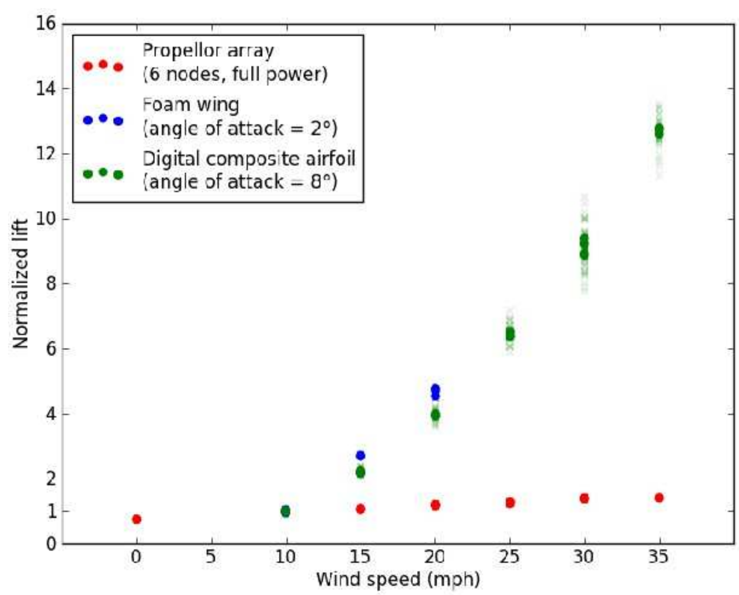
The initial question posed to the project team was the aerodynamic cost of using many small fans instead of one large one. To evaluate this, a networked programmable fan controller and an instrumented fan array was developed for wind tunnel measurements. These verified the approximately

square root improvement in efficiency with fan size, but an even greater degradation if the load, size, and speed are not matched. One of the opportunities for fan arrays is to be able to dynamically vary the number of optimized cells active, analogous to varying the number of active cylinders in an engine or fibers in a muscle.



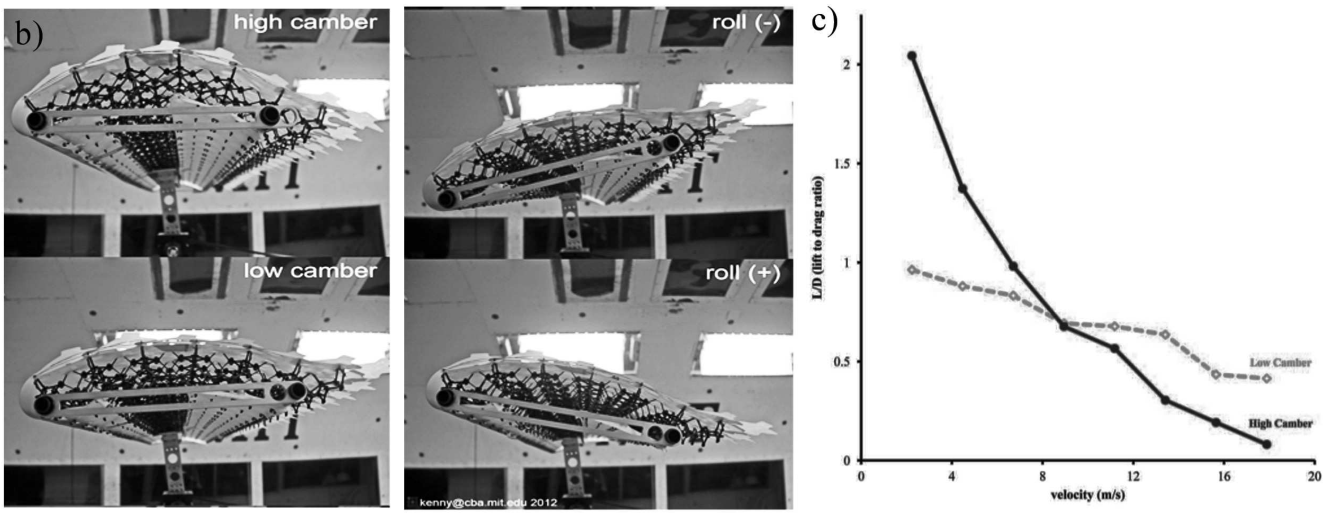
Fan array number and orientation dependence

The next question addressed was the aerodynamic interactions between neighboring cells. This was investigated as a function of fan spacing and orientation. For a linear array, lift was proportional to the number of fans, showing effectively independent air columns, and a beneficial optimum was seen for drafting, analogous to the V formation of a flock of birds.



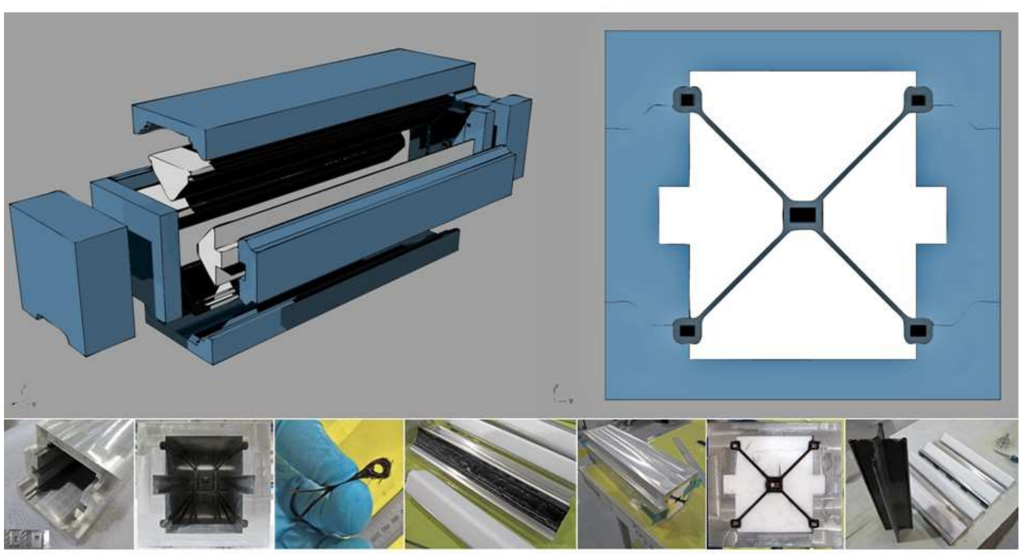
Lift versus velocity for a fan array and a wing

The question that followed was the lift dependence on forward velocity, asking whether collective effects would be beneficial or detrimental. This was studied with instrumented wind tunnel measurements on a fan array. These showed a weak linear improvement, from increasing mass transport through the fans. For comparison, a conventional wing was measured under the same conditions; this showed the much stronger quadratic dependence from redirecting the flow field.



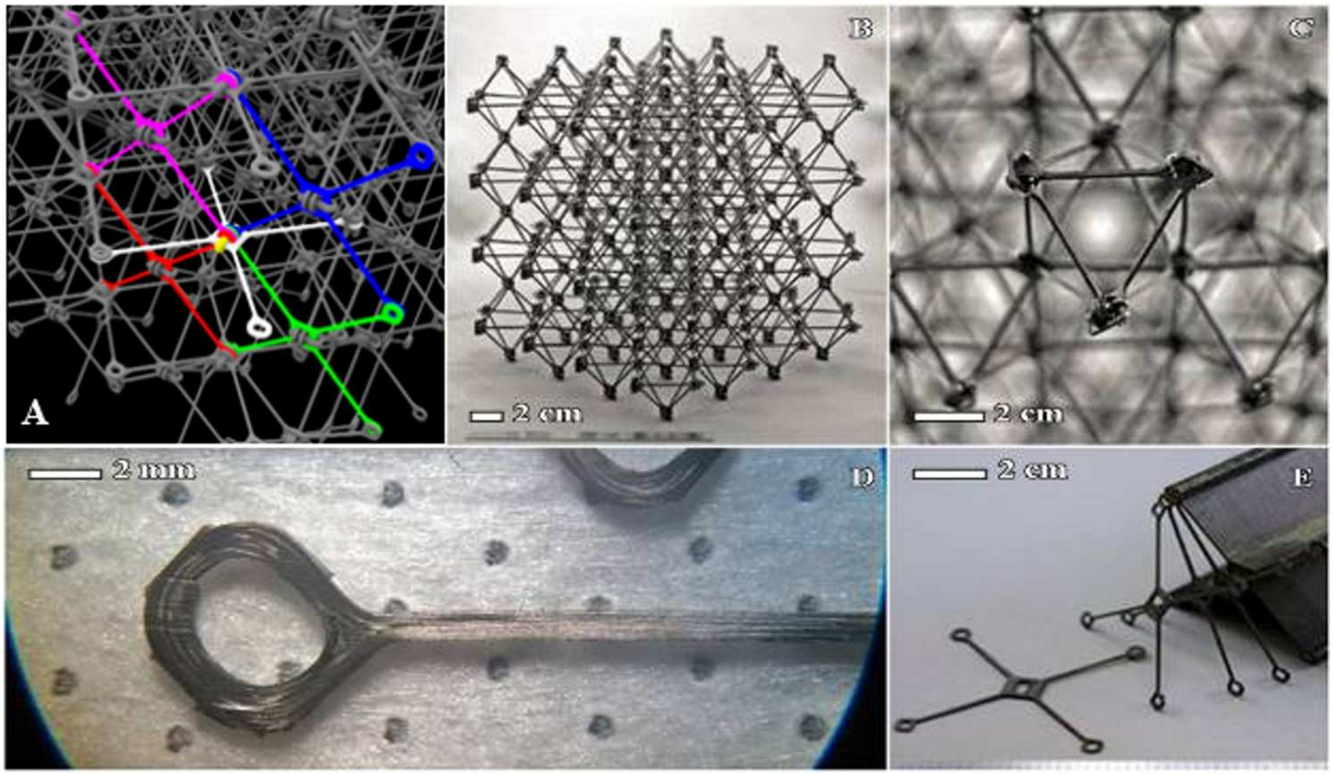
Continuously variable deformable wing lift and roll

These results pose a challenge for recommended future work: can a fan array continuously adapt its configuration to interpolate between static lift in hover and dynamic lift in forward flight? This will require introducing online optimization of both the spatial configuration and power distribution of the array.



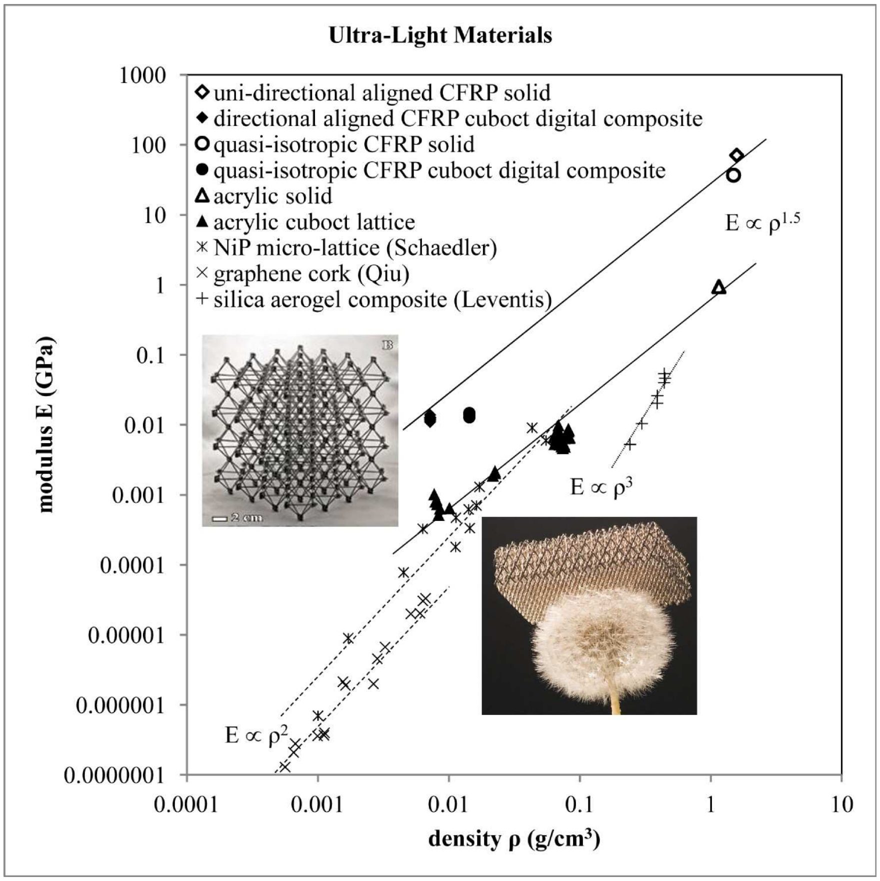
Oriented lay-up of carbon fiber loops

The modular construction of a programmable surface must be reflected in a reversibly-joined structural system. For making lightweight structures, conventional carbon-fiber construction relies on curing a matrix with long fibers that span the structure. Both joints between components and short fibers within components are avoided as weaknesses.



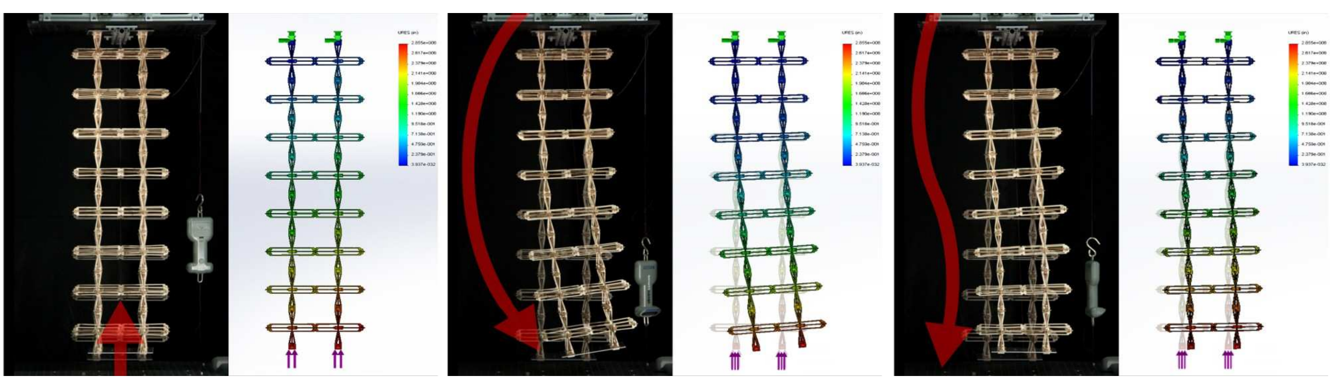
Reversible assembly of planar carbon fiber loops into vertex-connected octahedra

The most important result from this project was development of an alternative in response, discretely assembled “digital” composites. These are based on the concept of digital materials, which are assembled from a discrete set of parts reversibly joined in a discrete set of relative positions and orientations.



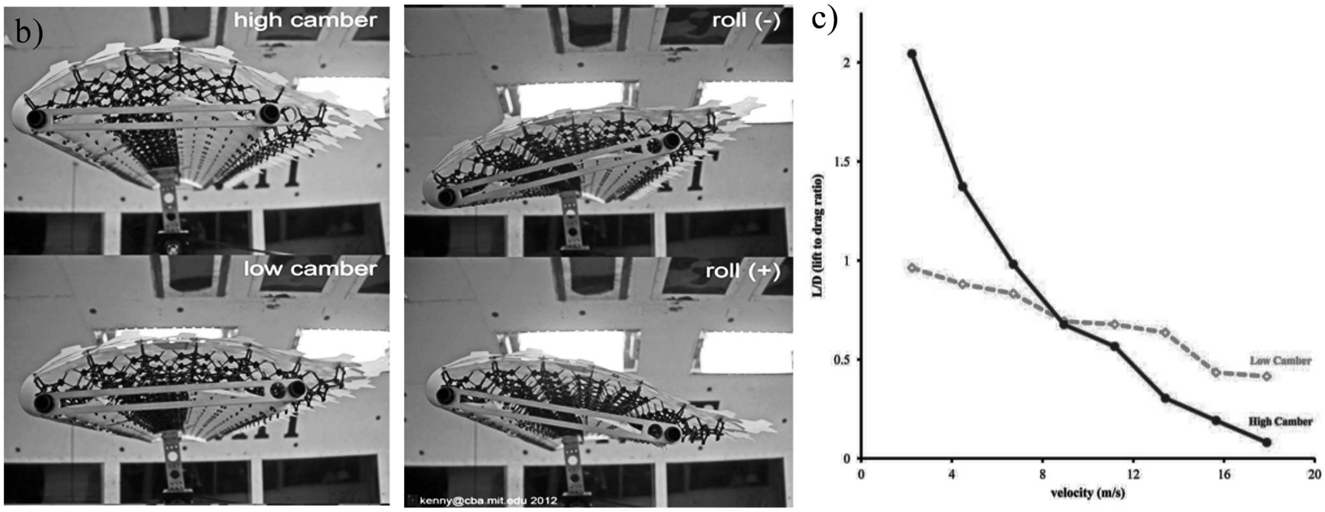
Modulus versus density of digital composites compared with existing ultralight materials

Instead of using either long or short fibers, digital composites link fiber loops to transfer forces through sparse space-filling volumes. A process was developed for the oriented lay-up of planar fiber loops. These were reversibly linked to form vertex-connected octahedra, a geometry chosen to be at the boundary between being under- and over-constrained [*Digital Cellular Solids: Reconfigurable Composite Materials*, Kenneth Cheung, *Ph.D. Thesis, MIT* (September 2012)].



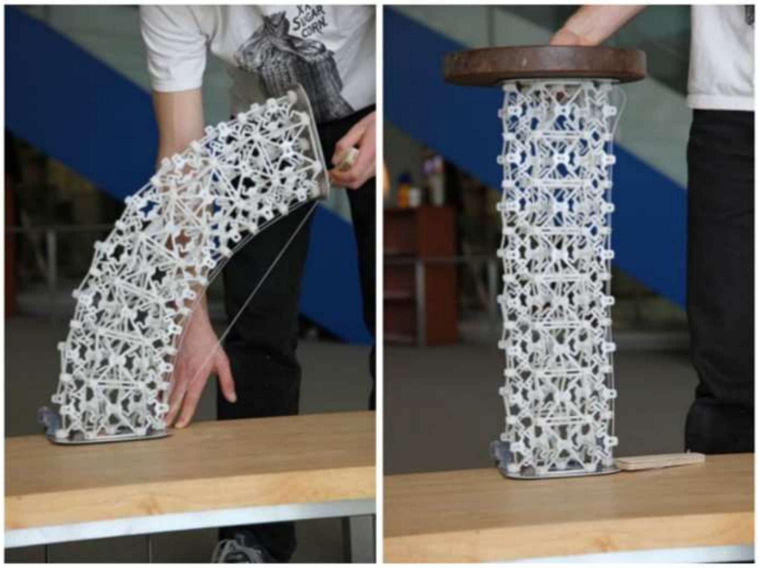
Compression, bending, and buckling of cellular structures under identical loads

The resulting structures were found to behave like an elastic solid, to fail incrementally rather than catastrophically, and to have a modulus more than an order of magnitude greater than existing ultralight materials [*Reversibly Assembled Cellular Composite Materials*, Kenneth C. Cheung and Neil Gershenfeld, *Science* (341), pp. 1219-1221 (2013)]. They extend the properties of carbon fiber into a previously inaccessible regime.



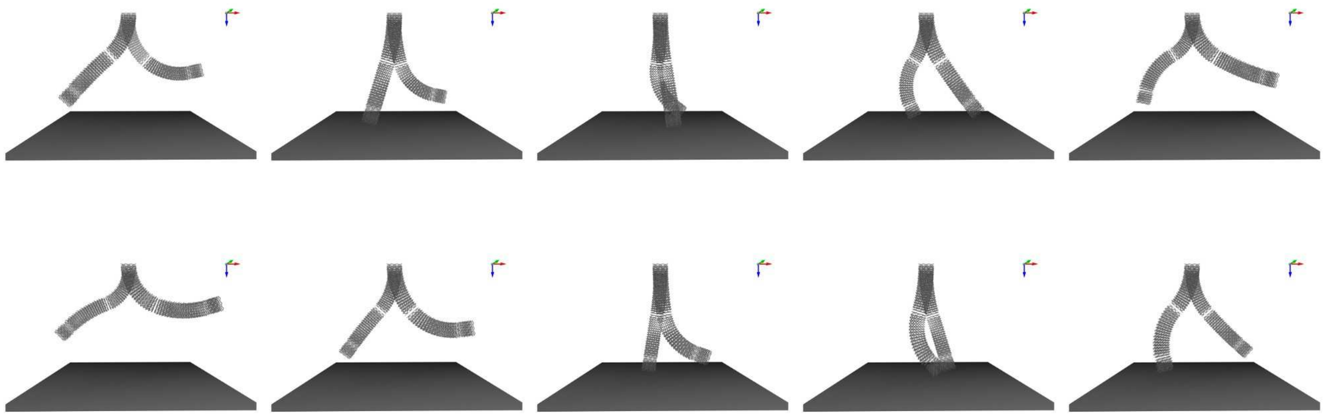
Pure lift and roll of a deformable wing

With the introduction of a flexural as well as rigid component, deformations can be designed by their relative placement. This degree of freedom was used to revisit the static wing measurements with a morphing wing. It was designed so that two boundary condition constraints could determine corresponding distributed degrees of freedom for lift and roll. This has seeded ongoing work on deformable aerostructures to improve their efficiency, agility, and manufacturability.



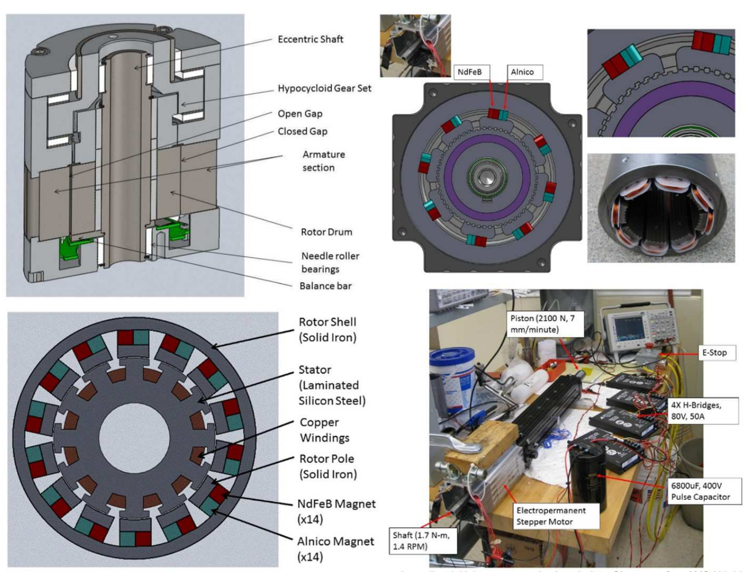
Anisotropic structure that can bend while carrying loads

The programmable surfaces project grew out of the study of programmable matter, and ended up developing deformable materials. Variable loading of flexural digital composites can be used to make mechanisms without conventionally moving parts. An example was assembly of an anisotropic structure that can bend easily while carrying loads, with a radius of curvature set by a tendon. Two of these could be linked like a double pendulum, driven by modulating two distance constraints for dynamically stable walking with elastic energy storage. This approach to actuated structures could extend the sizes, speed, and forces available to soft robotics, and is a recommended direction for future work.



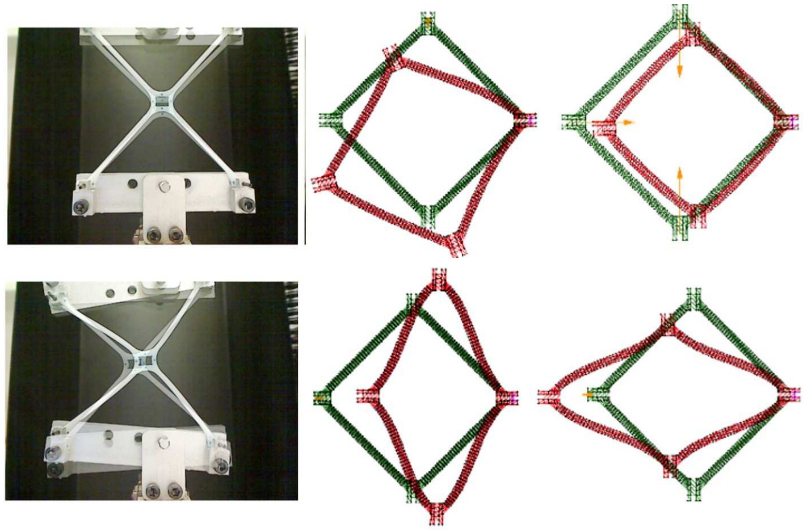
Walking with deformable materials

To drive these deformations, larger electropermanent motors were designed, based on their development by the project for coded folding. These offer static holding of the configuration without power, and high efficiency at low RPM without gearing. They are however less efficient for rapid motion; recommended future work will develop hybrid electropermanent motors that can continuously vary the remnant magnetization.



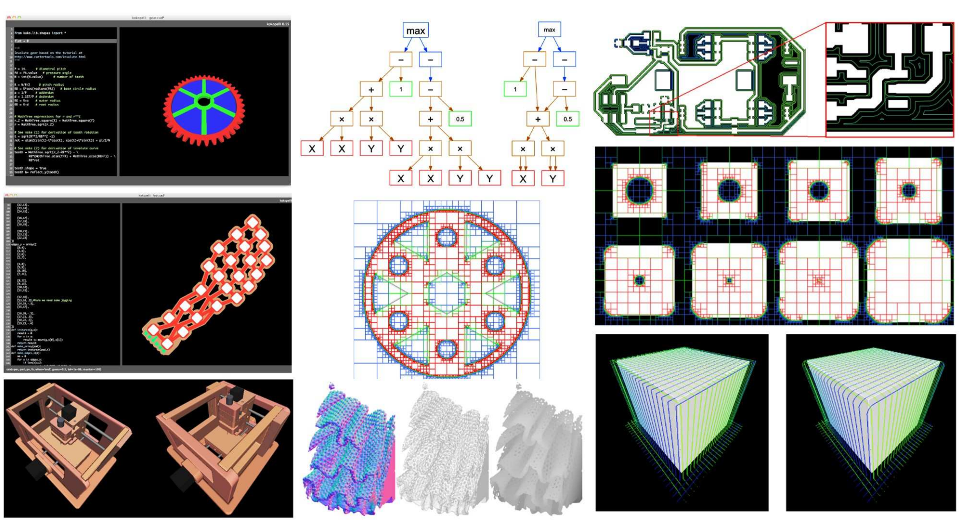
Electropermanent motor

Because digital composites are effectively constructed from physical finite elements, there is a natural hierarchical decomposition in their modeling. Once the part types are measured and modeled, they can be combined based on a discrete design description into a system model. Along with simplifying the design workflow, this equivalence offers a significant computational speed-up.



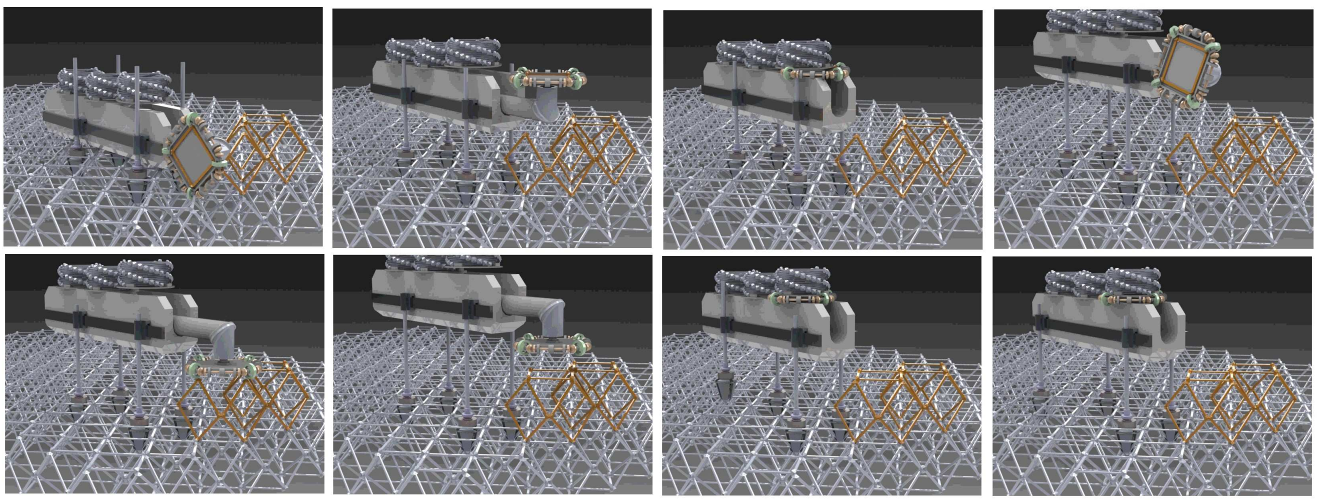
Measurement and modeling of physical finite elements

To design these structures, a geometry engine based on adaptively sampled distance fields (ASDF) was developed [*Hierarchical Volumetric Object Representations for Digital Fabrication Workflows*, Matthew Keeter, *Masters Thesis, MIT* (May 2013)]. This efficiently solves a functional satisfiability representation for a resolution-independent description of complex geometries, with a volumetric integration with rapid-prototyping workflows. Current work is investigating use of the hierarchical evaluation data structure as a multi-scale finite element model for part simulation.



Modeling with and adaptively-sampled distance fields

And to build these structures, work has begun on robotic assemblers. By linking the assembler to the structure that it is assembling in the same way parts are joined, arbitrarily large structures can be built by making only single cell steps within the structure. This discrete, relative robotics relaxes many of the usual challenges in robotics, including positioning, stability, and controls. The motivating application was assembly of digital composite aerostructures, but ongoing work is investigating areas ranging from “geoprinting” of landscape features for emergency preparation and response to manufacturing in space. Relative robotics in turn has many potential applications across the rest of robotics; recommended directions for future investigation include production of actuated robotic structures, locomotion in structured environments, and systems for industrial automation and logistics.



Relative robotic assembler for digital composite structures

Together, the results of the programmable surfaces project have linked more closely robotic structure and function, offering new ways to build robots, and new ways for robots to build.